CONCLUSION: "A GREAT REVOLUTION"

Sadi Carnot, the son of one of Napoléon's ministers of war and himself a soldier as well as a scientist, was convinced that one reason for Britain's victory in the Napoleonic wars at the beginning of the nineteenth century was its mastery of energy, specifically the steam engine. Determined to right that balance and impelled by deep curiosity as to how the steam engine actually worked, Carnot undertook a study that he published in 1824 as *Reflections on the Motive Power of Fire.* To his disappointment, it received virtually no attention at the time of publication. Carnot would die a few years later, at age 36, during a cholera epidemic with no knowledge of the profound impact his work would have. For he had written what was almost certainly the first systematic analysis of how man had actually harnessed energy. His work would prove a crucial input into the formulation of the second law of thermodynamics, and the "Carnot cycle" would become a staple of engineering.

But Carnot never doubted the wider significance of his analysis. He recognized that he was describing not only what happened inside an engine but also a transformation in human affairs. For the invention of "heat engines," using "combustibles," as he called them, "seemed to produce a great revolution in the civilized world." Humanity had broken the bonds that, except for rudimentary wind and water power, had been set by the muscles of man

and beast. It was indeed a revolution. More than a century after Carnot, Hyman Rickover actually tried to quantify what had been achieved. "Each locomotive engineer uses the energy equivalent to that of 100,000 men," said the admiral, "each jet pilot, of 700,000 men." Today that quantity would be all that much greater.

This harnessing of energy is what makes possible the world as we know it. The bounty can be measured in terms of virtually everything we do in the course of a day. But can we bet on that for the future?

The growth in world energy demand in the coming decades will be very large. The increase alone will be greater than all the energy that the world consumed in 1970. This increase is really a measure of success—of a more prosperous global economy, of rising standards of living, of billions of people moving out of poverty. In terms of oil, North America, Europe, and Japan have already reached peak demand. Because of demographics, increased efficiency, and substitution, their petroleum consumption will be flat or declining.

The story will be entirely different in emerging markets owing to the globalization of demand. Over the next couple of decades, two billion people—about a quarter of the world's population—will gain a significant "pay raise." They will move from a per capita income of under $10,000 a year to between $10,000 and $30,000 a year. Even with much greater energy efficiency, these rising incomes will mean much greater need for energy. How will that need be met? What kind of energy mix would make this possible without crisis and confrontation? The answers to these questions will be critical to the future.

The security issue that surrounds supply will continue to be a fundamental concern. Again and again, experience has demonstrated that the threats to reliability and security of supply can come in unexpected ways. Who thought that hurricanes in the Gulf of Mexico could lead to the biggest disruption of oil in American history and necessitate the dispatch of emergency oil supplies from Europe and Japan? And as economies and technologies change, security concerns take new forms. A decade ago, U.S.–Chinese relations were not a critical factor in global energy security. The Internet has ratcheted up the risks to the energy system, notably to the electric grid on which so much depends, including the very operation of the Internet.

The scale of energy flows from the Middle East and North Africa, and particularly the Persian Gulf, make that region central to the security of oil and natural gas supplies. The upheavals across North Africa and the Middle East have transformed the politics of the region and changed the relationship between governments and their people. At the same time, they have upended at least part of the geostrategic balance that has underpinned stability. This means greater uncertainty about the future of the region in which resources are so concentrated. And that kind of uncertainty and potential political volatility—and risks of crisis—increase concerns about vulnerability and energy security. The standoff over Iran's advancing nuclear program adds to the dangers and anxieties. These perceptions of greater risk translate into an increased risk premium in the price of oil, one that reflects the still-evolving new geopolitics of the region.

Policies related to access to energy and its production can have major impact on the timeliness of investment and the availability of supply—and thus on energy security. Policies can constrain supply and limit access. But the effects can also be positive, encouraging investment and technological advance. For years, it has been customary to say that the United States imports "two-thirds" of its oil. But today, at least, the United States imports only somewhat more than 40 percent of its oil. This is the result of greater fuel efficiency in the auto fleet, growth in domestic oil production, and increased use of biofuels. Technological advances have turned North Dakota into the second largest oil-producing state in the United States. The largest source of U.S. oil imports is a resource that did not really even exist on a commercial basis in the 1970s—Canadian oil sands.

The interaction of environmental concerns with energy will continue to shape the energy marketplace. The biggest question is climate change and carbon. Over 80 percent of world energy is supplied by what Carnot called the "combustibles"—carbon-based fuels. About 75 to 80 percent of world energy is expected to be carbon based two decades from now. The growing importance of the climate change question ensures that this ratio will be strongly challenged both politically and technologically as people strive to decarbonize.

While climate is the mega-issue, many other environmental questions will affect supply. Coal—the source of 40 percent of world electricity—is

challenged about other emissions. Two of the most important innovations that are particularly important to energy security—oil sands and shale gas—encounter determined opposition. Some seek changes in how these supplies are produced; some do not want them produced at all. How these issues are resolved will have decisive importance on the availability of energy and the security of supply. The accident at the Fukushima Daiichi nuclear site in Japan has led to a reconsideration of nuclear power around the world, as well as accelerating the drive for new designs and passive safety features.

A move away from Carnot's combustibles has already begun, but we are in the early stage of a transition—or at least a remixing of the energy mix. It represents, in one form, a shift from the carbon-based fuels, predominant since the beginning of the Industrial Revolution, to noncarbon-based fuels. It has a second form as well—transition to a more energy-lean world that operates at a much higher level of energy efficiency. In transportation, that shift to greater efficiency is already evident, both in miles per gallon and in the spread of hybrid technology. Biofuels will likely have a growing presence, but to gain more market share, they need to reach the second generation. Natural gas appears slated to make inroads as a transportation fuel. As for the electric car, it is too early to assess how far and how fast it will penetrate the global auto fleet.

One sector stands out in terms of future growth—electric generation. Worldwide electricity consumption could almost double over two decades. Renewables have played a role in power generation for years in the form of hydropower. But in many countries its growth is either circumscribed or blocked altogether by environmental opposition. Another existing technology for electric generation is geothermal power, which uses steam created by deep heat in the earth to drive turbines. While an important contributor in some regions, geothermal is limited by geology and the availability of the right kind of "hot rocks" underground.

The two big new noncarbon sources for generating electricity are wind and solar. They have registered great advances and much technological maturing since the "rays of hope" of the 1970s and early 1980s. Further advances, which will lower costs, are still to come. Already significant businesses in themselves, they are still small measured against the scale of the power business. They need to demonstrate that they can provide large-scale reliable electricity competitively—or society decides it is willing to pay additional costs through subsidies or with carbon charges. As these sources grow, how they are integrated into the overall grid becomes a more pressing question.

Are we on the edge of a new stage in the "great revolution" of energy? History demonstrates that energy transition generally takes a long time. It took almost a century before oil overtook coal as the number one energy source.

The pace of technological advance is not the only factor affecting the speed of any transition. Another factor is the law of long lead times. The energy system is large and complex, with an enormous amount of embedded capital. It does not turn over with anything like the speed of mobile phones. A power plant may have a sixty-year life span or even more. A major new oil field may require a decade or more between exploration and first production. Even the automobile fleet, despite the annual introduction of new models, does not change that quickly. It can take five years to develop a new model and then the fleet itself only turns over at the rate of about 8 percent in a typical year.

And yet things can change quickly. Shale gas took two decades to begin to register in the marketplace. But once it did, in a matter of just a few years, it dramatically changed the economics not just of natural gas but of competitors, from nuclear power to wind power.

By the early 2030s, overall global energy consumption may be 30 or 40 percent greater than it is today. The mix will probably not be too different from what it is today. Hydrocarbons will likely be somewhere between 75 and 80 percent of overall supply. One can imagine a host of factors—from political upheavals and military conflicts to major shifts in the global economy to changes in pricing and regulation or technological breakthroughs—that change this picture more decisively. But that law of long lead times still remains. It is really after 2030 that the energy system could start to look quite different as the cumulative effect of innovation and technological advance makes its full impact felt.

In the meantime, the elements shaping the future of energy are many, their interactions complex and sometimes confusing, and the differences in interests and perspectives considerable. All this makes forging a coherent

"energy policy" a challenging matter. Indeed, "energy policy" is often shaped by policies that are not even seen as "energy" but as "environmental." But history suggests that certain principles will be useful in making decisions in the future.

The first is to start with the recognition of the scale, complexity, and importance of the energy foundations on which a world economy depends, whether it is today's $70 trillion economy or a $130 trillion economy two decades from now. There is much to be said for an ecumenical approach that recognizes the contribution of the range of the energy options. Churchill's famous dictum about supply—"variety, and variety alone"—still resounds powerfully. Diversification of oil resources needs to be expanded to diversification among energy sources—conventional and "new." This represents a realization that there are no risk-free options and that the risks can come in many forms.

Energy efficiency remains a top priority for a growing world economy. Remarkable results have already been achieved, but technologies and tools not available in earlier decades are now at hand. The real advances will be embodied in behavior and value, but especially in investment—new processes, new factories, new buildings, new vehicles. There are many obstacles, ranging from financing to the fact that efficiency usually comes without the opportunity for good "photo ops." There is "no ribbon to cut."

Sustainability is now a fundamental value of society. Environmental priorities need to continue to be integrated into energy production and consumption. They should be analyzed and assessed in terms of impact and scale and cost-benefit analysis, assuring access to energy with appropriate environmental safeguards.

The whole sweep of Carnot's great revolution—from the steam engine start-up of James Watt in the eighteenth century and the oil start-up of Colonel Edwin Drake in the nineteenth century, to the latest cleantech start-ups spun out of Sand Hill Road, to whatever is currently bubbling in the lab—demonstrates that the advances of energy are the result of innovation and conviction. Developing new knowledge and "applying science" come with a price tag. But without sustained long-term support for the entire innovation chain, the world will pay a much larger price.

As we have seen in these pages, there are many parts to the quest. But fundamental to it, and underpinning everything else, is the search for knowledge, which advances technology and promotes innovation. Sadi Carnot captured a transcendent truth when he wrote about "the great revolution." But it was more a prediction when he penned those words for it was the very early days in this energy enterprise. What has been accomplished since could not possibly have been imagined. The challenges of meeting rising energy needs in the decades ahead, of assuring that the resources are available on a sustainable basis to support a growing world, may seem daunting; and, indeed, when one considers the scale, they truly are. Meeting them requires, among other things, the responsible and efficient use of energy, sound judgment, consistent investment, statesmanship, collaboration, long-term thinking, and the thoughtful integration of environmental considerations into energy strategies.

But what provides for reasoned confidence is the increasing availability of what may be the most important resource of all—human creativity. A famous geologist once said, "Oil is found in the minds of men." We can amend that to say that the energy solutions for the twenty-first century will be found in the minds of people around the world. And that resource base is growing.

The globalization of demand may be shaping tomorrow's needs. But it is accompanied by a globalization of innovation. The generation of knowledge and the application of science are becoming a worldwide endeavor; and the links and interactions, amplified by ever-widening information and communications systems, multiply the speed and impact of what can be accomplished. This means that the resource base of knowledge and creativity is expanding. This will fuel the insight and ingenuity that will find the new solutions.

This is not a blind faith, by any means. There is no assurance on timing for the innovations that will make a difference. There is no guarantee that the investment at the scale needed will be made in a timely way, or that government policies will be wisely implemented. Certainly, lead times can be long, and costs will have to evolve. As this story has shown, the risks of conflict, crisis, and disruption are inherent. Things can go seriously wrong, with dire consequences. Thus, it is essential that the conditions are nurtured so

that creativity can flourish. For that resource—creativity—will be critical for meeting the challenges and assuring the security and sustainability of the energy for a prosperous, growing world. That is at the heart of the quest; it is as much about the human spirit as it is about technology, and that is why this is a quest that will never end.